

Limiting the Photodegradation in Amorphous Silicon Solar Cells

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Abstract

One of the most serious impediments to the commercial development of amorphous silicon solar cells is the existence of photodegradation or the Staebler-Wronski effect. This effect was discovered nearly twenty years ago and considerable effort has since been devoted to methods of overcoming it, but so far no complete cure has been found. This paper will report on efforts to understand the mechanism of photodegradation and to find ways to limit or reverse its effect. A proposed model for the Staebler-Wronski effect will be presented as well as the results from studies of several methods suggested by the model for limiting or reversing photodegradation.

1 INTRODUCTION

One of the most serious impediments to the commercial development of amorphous silicon solar cells is the existence of photodegradation or the Staebler-Wronski effect (SWE) [Nevin et al., 1989; Wakisaka et al., 1992]. This effect was discovered nearly twenty years ago [Staebler and Wronski, 1977] and considerable effort has been devoted to methods of overcoming it, but so far no complete cure has been found [Nevin et al., 1989; Wakisaka et al., 1992]. The SWE manifests itself as a decline in the photovoltaic conversion efficiency of amorphous silicon (a-Si:H) solar cells with time under illumination [Wronski, 1984]. Typically the PV efficiency falls rapidly during the first few days of exposure to light, followed by a slower, exponential decay which gradually approaches an asymptote over a period of several months. Early samples showed a relative decay in the efficiency of up to 30% but some modern designs have reduced the SWE to around 10% [Zemen and Schropp, 1994; Guha et al., 1996]. Typically with the SWE a rapid decline is observed in the short circuit current after the cells are exposed to sunlight. The fill factor also falls, but not as much, while the open circuit voltage remains constant or even increases slightly [Uchida et al., 1983]. The SWE is also observed during ageing of the samples. Seasonal effects occur as the spectral composition of sunlight changes throughout the year.

The characteristics of the SWE suggest that it is due to the creation of traps and recombination sites in the a-Si:H due to the effects of sunlight on the material [Crandall, 1991]. Crystalline silicon also exhibits a decline in efficiency with exposure to sunlight as a result of radiation damage [Hawkins and Muirhead, 1996], but this effect is much slower than the SWE seen in a-Si:H. Over a number of years we have carried out a careful study of photodegradation in a-Si:H in order to understand the mechanism of the SWE. Infrared absorption spectroscopy, combined with light soaking and theoretical modelling has provided insight into the mechanism of photodegradation enabling us to develop an explanation for the SWE [Clare et al., 1996a, 1996b].

Our theory explains the SWE in terms of the breaking of Si-Si and Si-H bonds in the upper layers of the a-Si:H solar cells under illumination. Some of these broken bonds fail to repair themselves and they become dangling bonds or shallow traps just above the valence band and in the bandgap of the a-Si:H material. The presence of an excess of dangling bonds in the surface of the material drives hydrogen from the bulk to the surface where it neutralises some of those dangling bonds. This leads to an excess of hydrogen in the *p*-layer which in turn increases the open circuit voltage of the solar cell. However the movement of the hydrogen atoms leaves behind additional dangling bonds in the bulk and these form trap sites for the electrons which are generated by the sunlight. Consequently the carrier density declines and the short circuit current is diminished. Eventually once the density of defect sites is similar in the surface and the bulk this process becomes self-limiting. This point marks the end of the rapid decay phase of the SWE. Under further illumination a slower decay in efficiency is observed, similar to that in crystalline silicon. In the second phase of the SWE the sunlight produces further radiation damage in the surface layer but the presence of a high concentration of hydrogen improves the repair mechanism and limits the subsequent decay of the solar cell. This theory has been tested by analysing the infrared spectra of a-Si:H films during an extended period of light soaking and also after annealing [Clare et al., 1996a].

2 LIMITING THE STAEBLER-WRONSKI EFFECT

Our theory appears to explain all of the known characteristics of the SWE and it suggests a number of possible methods of limiting its effect. In particular the following approaches appear to offer some promise.

2.1 Use of Light Trapping

The migration of hydrogen atoms to the surface layers is promoted by the non-uniform illumination of the material. The upper surface receives the most intense, and most energetic, radiation and most of the bond breaking occurs there. This results in a chemical potential which drives the hydrogen from the bulk to the surface. This potential could be reduced by illuminating the material more uniformly by reflecting the transmitted light from the back surface and trapping it in the device. A textured substrate provides an ideal means of doing this. An added benefit is that light trapping increases the utilisation of the light by the device and this should also yield a higher initial efficiency. We expect that a-Si:H solar cells with light trapping included will show slower and less photodegradation than flat plate samples.

2.2 Annealing

It is well known that annealing of a-Si:H devices at ~150°C in the dark reverses the SWE [Nevin et al., 1989; Wronski, 1984; Crandall, 1991]. Our studies have confirmed this also [Jennings et al., 1995; Clare et al, 1996a]. The reason for this reversal is that annealing provides thermal energy which excites lattice vibrations and these promote the healing of the dangling bonds in the bulk of the device. Annealing does not totally reverse the effects of the SWE but it does reduce the number of defects in the lattice and therefore restores most of the short circuit current and efficiency. The problem with using annealing in practise is that it is impractical to anneal degraded modules at 150°C in the field. They could be dismantled and returned to the factory for treatment but the cost would be prohibitive.

2.3 Hydrogen Enrichment of the *p*-Layer

Increasing the hydrogen content of the uppermost *p*-layer can be expected to have two beneficial effects. It will increase the open circuit voltage [Okamoto, et al., 1994] and provide a larger pool of hydrogen atoms to promote healing of the lattice, thus reducing the demand for hydrogen from the bulk. Increased hydrogen may be incorporated in the *p*-layer by depositing it at a lower temperature or by altering the gas mixture or power density in the glow discharge during deposition. A related approach which is gaining in popularity is to produce a microcrystalline *p*-layer by using hot wire deposition. The microcrystalline material is less susceptible to radiation damage and thus more resistant to the Staebler-Wronski effect [Schropp et al, 1996].

2.4 Electric Field Effects

The existence of an internal electric field in the solar cell promotes the migration of protons from the bulk to the p -layer. This will be accelerated by light soaking. It should therefore be possible to reverse the flow of protons to the upper surface by forward biasing the p - i - n -device to reverse the internal field. Then, under illumination, the internal field will drive the protons back into the i -layer where they may attach themselves to dangling bonds and neutralize them. This should reduce the number of traps for electrons in the i -layer but it will create an equal number of traps in the p -layer and therefore little improvement in performance may be obtained unless the defects in the p -layer are repaired. This could possibly be achieved, for example, by infrared annealing in field operations. Thus electric field treatment is only likely to succeed if it is combined with some form of annealing.

If a successful approach is found for reversing the Staebler-Wronski effect in a-Si:H solar cell devices, and it could be implemented under field conditions at minimal cost, it would greatly enhance the long-term performance of a-Si:H solar cells. We have therefore carried out an extensive study of these approaches to test their effectiveness.

3 EXPERIMENTAL METHOD

The glow discharge (GD) p - i - n a-Si:H devices used in this study were prepared in a capacitively coupled (13.56 MHz) radio frequency glow discharge system. Typical GD depositions were performed at temperatures between 220°C and 250°C and at a power of 9 watts and the a-Si:H material was deposited onto flat or textured Indium Tin Oxide (ITO) on glass substrates. After deposition of the p - i - n material the samples were transferred to a bell jar system where 0.047m² aluminium spots were deposited on the non substrate side.

The light soaking experiments were carried out in the laboratory using a solar simulator constructed from an overhead projector bulb and optical system which produced intensity corresponding closely to AM1 sunlight. The samples were mounted on a specially-designed holder which was water-cooled to prevent overheating during light soaking. Electric field treatments were carried out in a separate, but similar system to that used for the degradation, in which a forward or reverse DC bias could be applied to the samples during illumination by light of AM1 intensity. This system is shown in Figure 1. Like the light soaking system the samples were mounted on a specially-designed holder which was water-cooled to prevent overheating during illumination and electric field treatment. During either photodegradation or electric field treatment the cell temperatures were monitored and did not exceed 40°C.

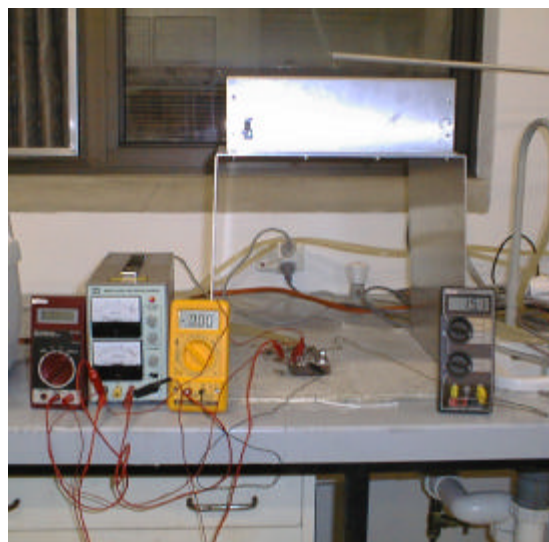


Figure 1 - Photo of system for applying electric field treatments to a-Si:H solar cells.

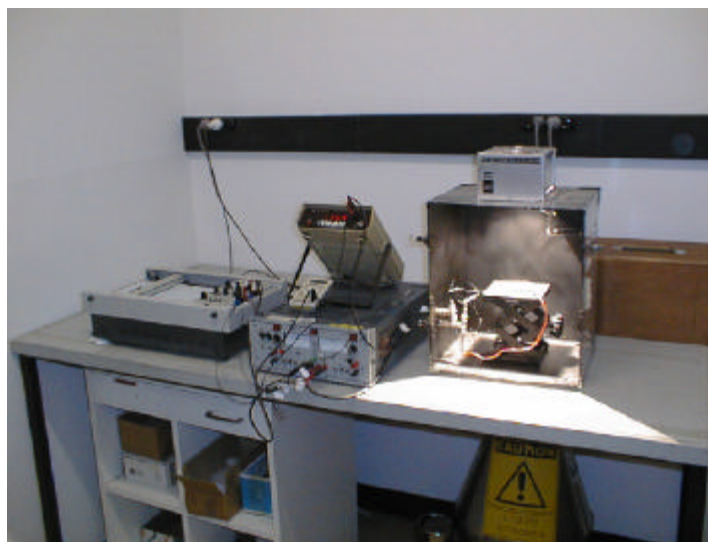


Figure 2 - Photo of system for measuring current-voltage characteristics of a-Si:H solar cells.

Before and after photodegradation or treatment, the samples were tested by measuring their current-voltage (IV) characteristics in our measurement system. For these measurements we used a tungsten projector lamp enclosed in a lightproof box which was calibrated using a standardization cell to give irradiance equal to AM1. The voltage from a variable Bipolar DC power supply was then applied across the cell. The resulting current output from the cell at a given voltage was measured by a digital microammeter. The output values for voltage and current were recorded on graph paper on an electronic chart recorder. This system is shown in Figure 2. By varying the applied voltage across the sample, the I-V dark characteristic was obtained with the illuminated characteristic being obtained in the same way when the sample was illuminated by the light source. The values of short circuit current I_{sc} , open circuit voltage, V_{oc} , voltage at maximum power point, V_{max} and current at maximum power point I_{max} were then determined from the plotted dark and light characteristics. Values for fill factor and efficiency were then calculated from these measured values.

4 RESULTS AND DISCUSSION

4.1 Light Soaking Experiments

A series of experiments were carried out on samples deposited on flat and textured ITO substrates which were exposed to simulated sunlight of AM1 intensity for periods of up to 500 hours in order to monitor their degradation due to the SWE. The IV characteristics of a number of spots on each sample were measured at AM1 intensity before, during and after light soaking. Some of these results are shown in Figure 3. This figure shows the results of the experiments for three pairs of samples on flat ITO and textured ITO substrates which were deposited under conditions which were identical for each pair, but could differ between pairs. A number of spots on each cell were tested for consistency and several of these are shown for each cell.

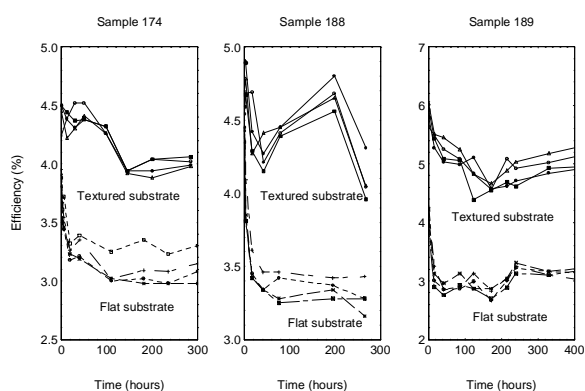


Figure 3. Efficiency versus time for three matched pairs of *p-i-n* a-Si:H solar cell devices light soaked under open circuit conditions at an intensity of AM1 sunlight. Dashed curves are flat ITO, solid curves are textured ITO.

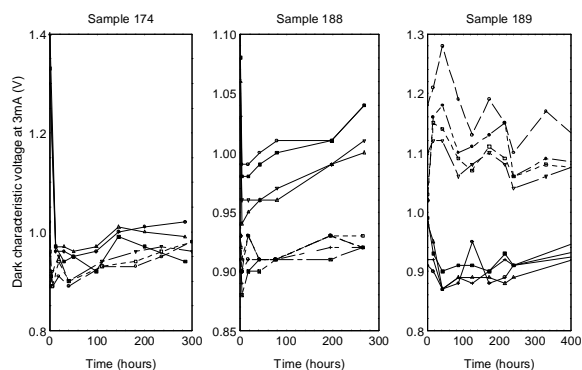


Figure 4. Dark characteristic voltage versus time for three matched pairs of *pin* a-Si:H solar cell devices light soaked under open circuit conditions at an intensity of AM1 sunlight. Dashed curves - flat ITO, solid curves - textured ITO.

Some general observations may be drawn from these results.

1. The initial degradation in the PV efficiency is rapid, occurring in the first 20 or so hours, followed by a much slower decay, with some fluctuations observed over the following weeks.
2. The flat plate samples appear to decay more rapidly and to a greater extent than the textured samples.
3. There is some variation in behavior between different spots on the same sample and between different samples but a common overall pattern of photodegradation is observed.

These results confirmed our expectation, based on our theory of the SWE, that a-Si:H solar cells deposited on textured substrates would be more stable than those deposited on flat substrates. According to our theory [Clare et al., 1996b] this is a consequence of the more uniform illumination of the cell in the case of the textured substrate, which leads to a more uniform distribution of dangling bonds in the device. Thus the chemical potential driving the hydrogen atoms to the surface is minimised by the use of light trapping techniques. The use of optical admittance analysis, combined with optimal texturing of the substrate could maximise the light trapping in these devices. This would have the double benefit of maximising the photon efficiency of the device and minimising the photodegradation.

Figure 4 shows the change in the dark characteristic voltage at 3mA, which is plotted rather than the dark current threshold as it reflects the changes in the dark current threshold, but is easier and more reliable to measure. From Figure 4 it can be seen that the dark current threshold, which is normally around 0.6eV for crystalline silicon, shows an initial rapid drop then a slow increase with time as illumination continues for both the samples on flat ITO and those on textured ITO. This suggests further agreement with our theory for the SWE as it is consistent with the illumination promoting the migration of protons from the *i*-layer to the *p*-layer leading to a decrease in the dangling bonds in the surface. Such a change in the surface *p*-layer would result in the decrease in the dark current threshold (dark characteristic voltage at 3mA) seen in the results of Figure 4.

These degradation studies provided the basis for the subsequent experiments which were aimed at investigating methods of restoring the photovoltaic efficiency of degraded devices.

4.2 DC Electric Field Treatments

The existence of a space-charge barrier is essential for the operation of a solar cell. However, in the case of a-Si:H, the barrier can facilitate the migration of protons towards the *p*-layer, thus producing defects in the *i*-layer which act as traps for the free electrons generated by illumination. We therefore examined the effect of applying forward and reverse DC biases (between 0 and 3 V) to *p-i-n* devices while they were exposed to simulated sunlight of approximately AM1 intensity for various periods of time. The aim of this study was to attempt to reverse the internal field in the device in order to promote the migration of hydrogen atoms from the *p*-layer to the *i*-layer. Typical results of these experiments are presented in Figures 5 and 6.

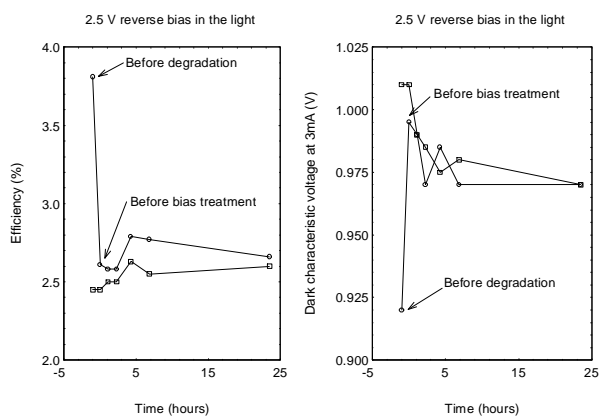


Figure 5. Plots of efficiency and dark voltage at 3mA for a light soaked and degraded a-Si:H sample exposed to 2.5 V reverse bias under illumination.

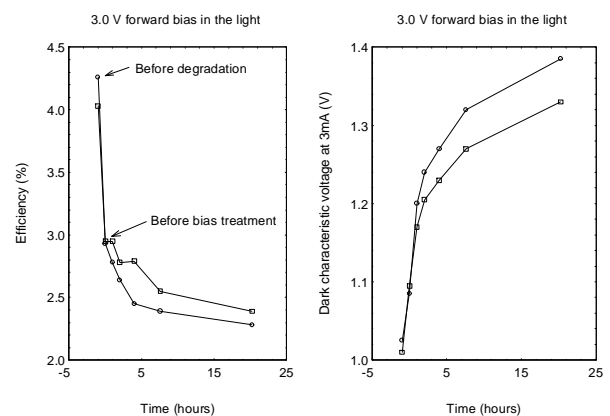


Figure 6. Plots of efficiency and dark voltage at 3mA for a light soaked and degraded a-Si:H sample exposed to 3.0 V forward bias under illumination.

It is apparent from these figures that long term exposure (in the region of 20 h) to simulated sunlight under forward bias causes further degradation of the sample, with a loss of the cell efficiency. The rate of degradation increases with increased forward bias. For reverse bias under illumination the degradation was found to either remain constant or be reduced slightly with increasing reverse bias. Short term exposure to illumination (less than 1 hour) at 2 V forward bias was found to have no effect on either the dark or illuminated characteristics. It can be seen in Figures 5 and 6 that the dark characteristic voltage at 3mA shows a significant increase with time as illumination continues under forward bias, while the opposite occurs under reverse bias, with a noticeable (smaller) decrease. This indicates that the forward bias is promoting the migration of protons from the *p*-layer to the *i*- or *n*-layer leaving behind dangling bonds in the surface which increase the threshold voltage in the dark. The effect on the dark current threshold was found to increase with the magnitude of the bias voltage. From these results we conclude that while both forward and reverse bias treatments at DC voltages in the range 0 to 3V have an effect on the a-Si:H devices neither is effective in reversing the SWE to any significant degree.

Other samples were subjected to DC electric field bias in the dark and a typical result is shown in Figure 7. The results of these experiments indicate that some changes, similar to those in the corresponding illuminated samples, occur in the samples treated in the dark but these changes are not as great.

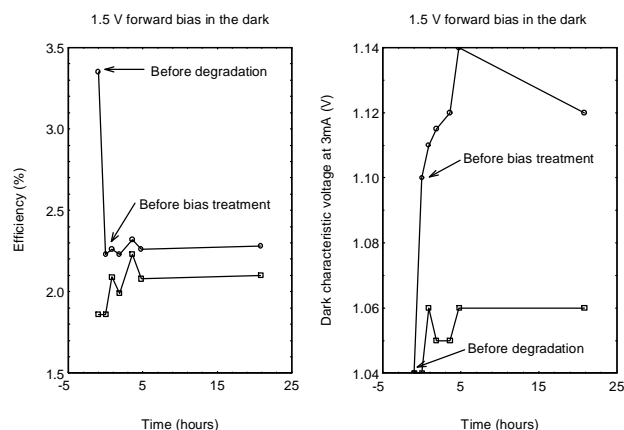


Figure 7. Plots of efficiency and dark characteristic voltage at 3mA for a light soaked and degraded a-Si:H sample exposed to 1.5 V forward bias in the dark.

The results obtained from these DC bias studies show that forward bias under illumination can in fact increase the SWE while in the case of reverse bias under illumination there appears to be very little change. Both forward and reverse DC bias under illumination are seen to have an effect on the dark current. Neither forward nor reverse bias DC in the range of 0 to 3V in the dark appear to have much effect on either the light or dark characteristics. Therefore while applying a DC bias in the range of 0 to 3V to a photodegraded a-Si:H cell whilst illuminated does not reverse the SWE, it does affect the fundamental structure and electronic characteristics of the cell as seen in the changes in the dark characteristic.

Carlson and Rajan [1997] have recently reported the reversal of light-induced degradation in amorphous silicon solar cells by an electric field treatment. To achieve significant reversal of the light-induced degradation however required typically 30 minutes exposure to 60 suns at -6V at 125° C. Carlson and Rajan [1997] conclude that it does not seem practical to use a strong reverse bias in the presence of intense illumination to reverse the degradation since the energy requirements are so large. To quote Carlson and Rajan [1997], "Under these circumstances, it would take about 6 years of exposure to sunlight for a 10% efficient cell to generate the same amount of energy".

5 CONCLUSIONS

The results of this work have confirmed our expectation, based on our theory of the SWE, that a-Si:H solar cells deposited on textured substrates would be more stable than those deposited on flat substrates. We have also shown that applying either a forward or reverse DC bias in the range of 0 to 3V to a photodegraded a-Si:H cell whilst illuminated does not reverse the SWE. It was shown that these treatments do however affect the fundamental structure and electronic characteristics of the cell as observed in changes in the dark characteristic. The results of these experiments on the photodegradation and attempted repair of a-Si:H solar cells reveal that there are possibly several useful ways of reversing or reducing the SWE.

- The use of textured substrates appears to be effective in reducing the size and rate of photodegradation in a-Si:H solar cells. Combined with optical admittance analysis this approach can yield not only higher initial efficiencies but greater stability under illumination.
- The use of DC electric fields alone on degraded samples, although inducing changes in the characteristics of the degraded films do not appear to be a promising method of reversing photodegradation in the field. If electric field effects could be combined with gentle annealing to remove damaged bonds in the surface there may be significant recovery. This approach will be investigated by using various forms of irradiation of the surface together with electric field treatment under illumination.
- Another promising approach for reducing the SWE is to use hydrogen enrichment of the *p*-layer during the deposition of the *p-i-n* device. This will enhance the open circuit voltage and provide a larger pool of hydrogen atoms to neutralise the damaged bonds produced by solar radiation and such samples will have less tendency to drive hydrogen atoms from the bulk to the surface under illumination.
- Another approach would be to deposit a microcrystalline silicon *p*-layer during the deposition of the *p-i-n* device. This material is much more resistant to photodegradation than a-Si:H.

These approaches require further investigation in order to demonstrate their effectiveness.

6 ACKNOWLEDGMENTS

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